HEAT TRANSPORT AND THERMAL EXPANSION OF ELECTROCHROMIC GLAZING SYSTEMS WITH VOLTAGE CONTROLLED TRANSMISSION DUE TO SOLAR IRRADIATION[1]

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Electrochromic glazings consist of two glass panes coated firstly with an electroconductive layer and secondly with an electrochromic film. The two glass panes are laminated together with an ion conducting polymer foil. In response to an applied voltage the electrochromic films change their absorptance and reflectance. Such electrochromic glazings are for instance ideal suited for architectural applications to prevent overheating of rooms and to protect against glare of sun. For this purposes a thorough understanding of the heat transport and the optical and thermal radiative properties of the system is essential. Furthermore the thermal expansion and eventually the induced stresses within the laminated system are of interest. To meet this demands the solar absorptance of the electrochromic glazings at different tinted states were measured using an UV-VIS-NIR spectrometer. Furthermore the thermal expansion coefficients of the glass materials were determined by a push-rod dilatometer. Then the instationary coupled conductive and radiative heat transfer due to solar irradiation were calculated for various pane configurations and depending on the transmittance of the electrochromic film by finite element analysis. Starting from the resulting instationary temperature fields we finally computed the stress and strain states within the laminated glazing system.

KEY WORDS: electrochromic glazing; solar transmittance; solar reflectance; heat transport; temperature stress.

1. INTRODUCTION

In the recent years research in the field of electrochromic films led to the development of a new type of a glazing system with voltage controlled transmittance [1]. It is possible to switch the visible light transmittance from 0.08 at the colored to 0.75 at the bleached state with very low electric energies. This is a reversible process. A multitude

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of different colors such as blue, green, red, brown, violet and grey is provided in dependence on the electrochromic film composition. The switching time between full colored and bleached state lies in the range of 30 seconds to 5-10 minutes.

There is a tremendous application potential for such electrochromic glazings. Switchable filters for light and heat within optical instruments, rapid responding sunglasses and large area information displays are feasible. In the car industry the adoption of electrochromic systems in sunroofs with overheating protection and for windshields and rear view mirrors with glare protection is advantageous. Architecture represents a further wide application field. Electrochromic glazing can be used as smart window without any mechanical sun protection systems which can change gradually the transmittance in response to the intensity of the solar radiation according to Fig. 1. Such windows have the capability to prevent overheating of rooms during intense sunshine periods. Less climatisation effort with valuable energy savings is the result. Protection against glare and electromagnetic radiation are additional advantages.

To enable precise computations of the solar heat input into the room the transmittance and absorptance data of the electrochromic glazings have to be measured. These data are also essential for the calculation of the instationary temperature fields within the electrochromic glazings during solar irradiation with varying intensity. High temperatures are expected especially in the colored state of the electrochromic glazing. Instationary temperature fields always force thermal stresses in the material. To ensure a damage free function of the glazings the maximal stresses due to solar irradiation in some critical cases have to be calculated.

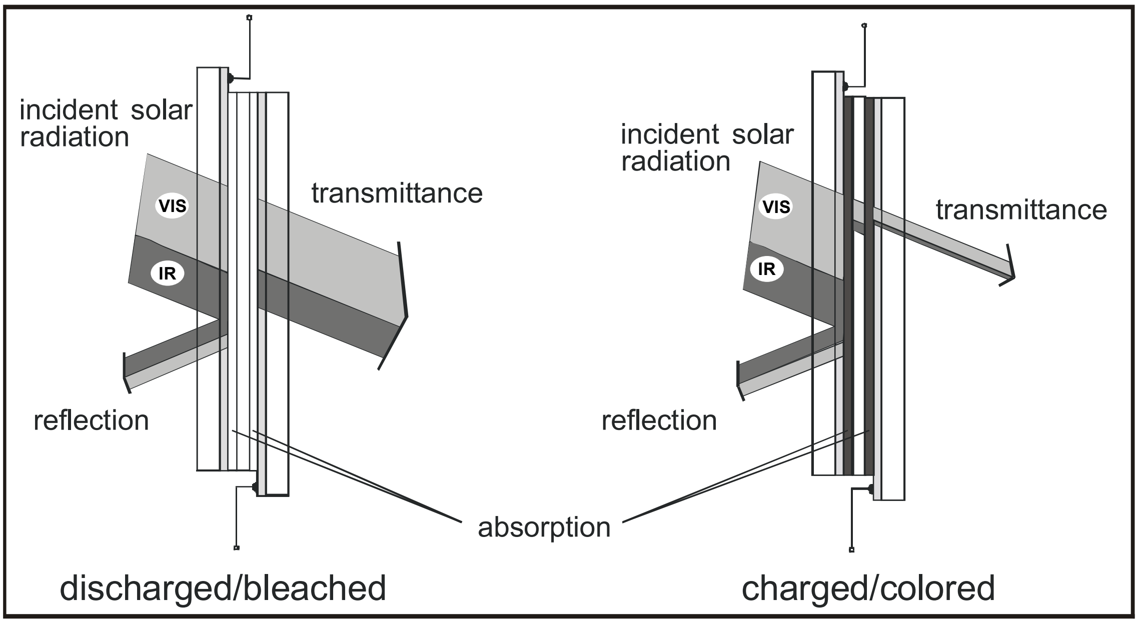

Fig. 1. Schematic of the controlled transmittance of electromagnetic radiation by means of the electrochromic glazing.

2. ELECTROCHROMIC GLAZING SYSTEM - DESIGN AND FUNCTION

A schematic of the electrochromic glazing system is shown in Fig. 2. Two glass panes with a transparent electroconductive film (e.g. fluorine-doped tin oxide) were secondly coated with complementary electrochromic layers using an electrochemical deposition technology. These layers consist of Prussian Blue and tungsten oxide respectively in the present case. Both films can be switched between a blue colored and an uncolored state. Finally the glass panes were laminated together with an ion conductive polymer foil.

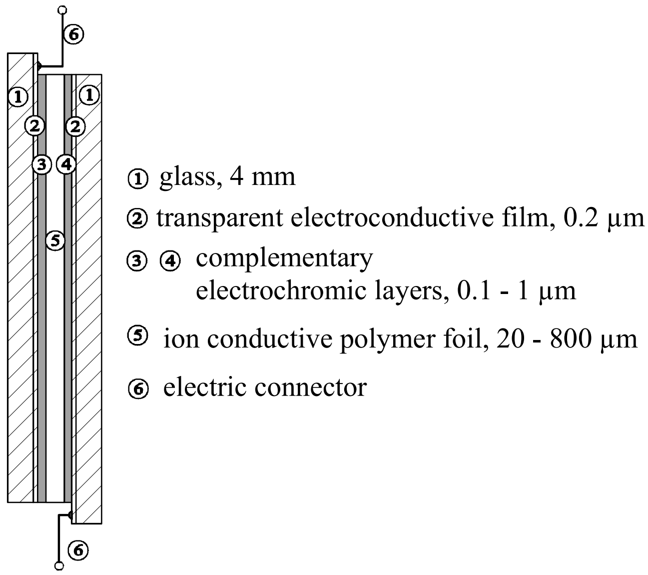

Fig. 2. Schematic of the electrochromic glazing.

If a d.c. voltage in the range of 1.2 V to 2.4 V is applied, oxidation and reduction reactions in the electrochromic layers are induced which are accompanied by insertion or extraction of ions. Due to this process these layers change their transmittance especially for visible light and near infrared radiation. The Prussian Blue layer is coloring with oxidation and ion extracting whereas the tungsten oxide layer is coloring with reduction and ion reception. The energy necessary for full coloration is only about 200 $Ws \cdot m^{-2}$. If the polarity of the applied voltage is reversed the electrochromic films are bleaching.

3. SOLAR TRANSMITTANCE

To gain data for further temperature field calculations the transmittance and reflectance data of the electrochromic glazing at different colored states are necessary. The reflectance and the transmittance in the wavelength range of the solar radiation (280 nm to 2500 nm) at 20°C were measured using an UV-VIS-NIR spectrometer (type Perkin-Elmer Lambda 19). These measurements were performed at the full bleached and the full colored state respectively. The results are shown in Fig. 3 and Fig. 4. The solar transmittance T_{solar} and reflectance R_{solar} as well as the visible transmittance T_{vis}

and reflectance R_{vis} were derived from the spectrometer data according to the European standard EN 410 [2].

The time-dependent reflectance and transmittance curves of the glazing in the wavelength range from 380 nm to 780 nm meanwhile a coloring and bleaching cycle were measured by means of a diode-array spectrometer (type IKS X-dap). The results are shown in time steps of 20 seconds in Fig. 5 and Fig. 6.

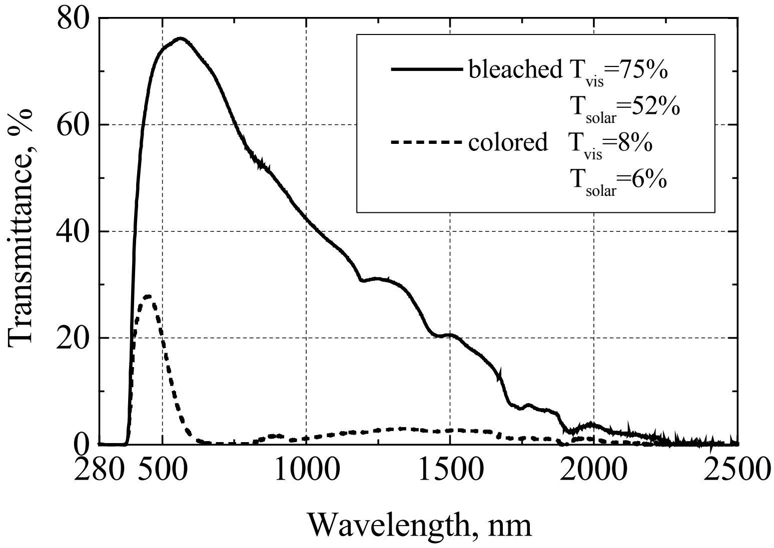

Fig. 3. Transmittance of the electrochromic glazing.

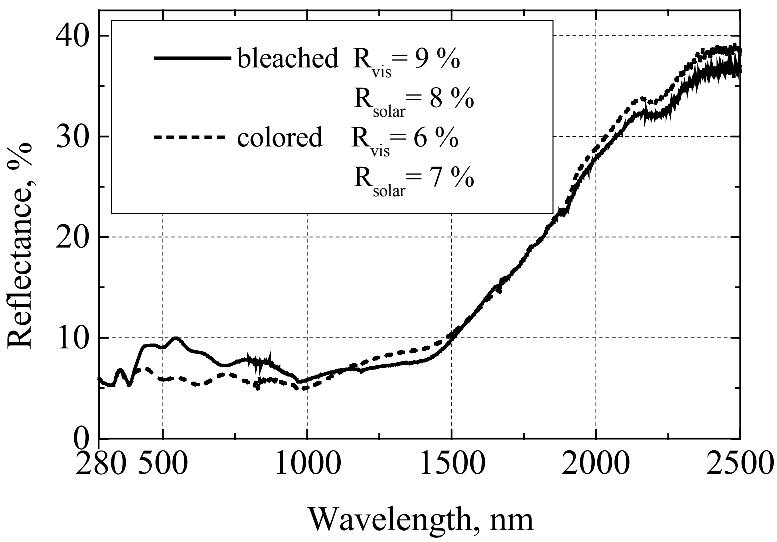

Fig. 4. Reflectance of the electrochromic glazing.

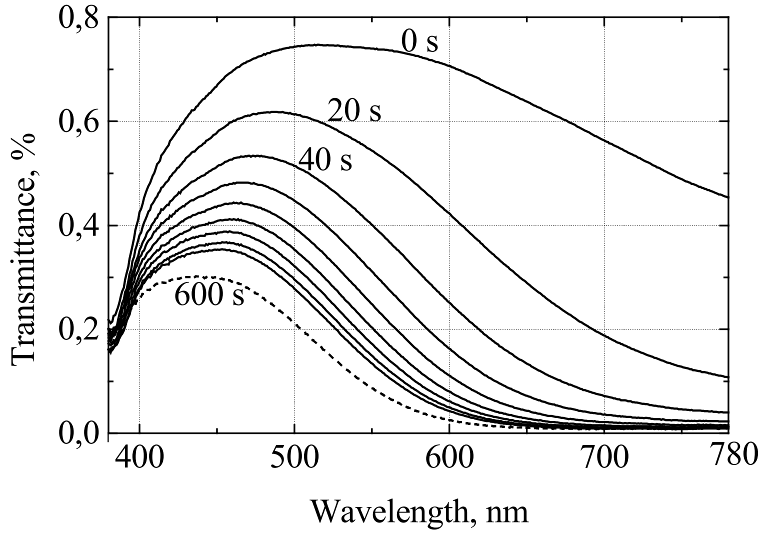

Fig. 5. Time dependent transmittance of the electrochromic glazing during coloration.

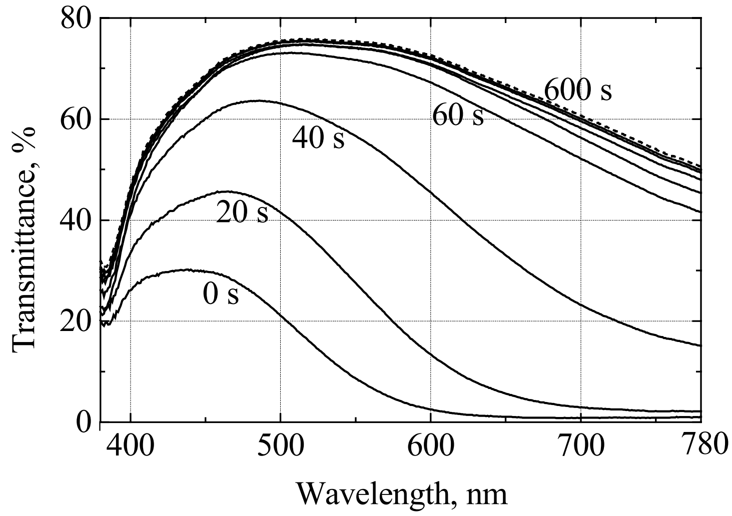

Fig. 6. Time dependent transmittance of the electrochromic glazing during bleaching.

4. TEMPERATURE FIELDS DUE TO SOLAR IRRADIATION

To estimate critical stress states of the glazing at sudden solar irradiation the instationary temperature fields for test samples with an area of $(0.25 \times 0.25)\ m^2$ under the assumption of several partly shaded cases were calculated. One surface of the glazing is supposed to be subjected to direct solar radiation ramping from 0 to 800 W·m^{-2} within 600 s. After a following constant radiation time period of 600 s the irradiation power declines again to 0 W·m^{-2} within 600 s. This solar load is a good approach to real conditions. For the internal heat generation inside the electrochromic layers due to absorption of solar energy the most critical case of the full colored state is considered. In this case the solar reflectance is R_{solar}=0.07 and the solar transmittance T_{solar}=0.06 and consequently a maximum heat flux density of 696 W·m^{-2} is absorbed. Under neglect of the absorptance within the first glass pane, which is less than 5 %, a heat source region between the glass panes with a thickness of 200 µm was assumed. The surfaces of the glazing are considered to radiate to ambient temperatures of 10°C and 20°C respectively with a hemispherical emissivity of 0.84 [3]. Furthermore there is a heat exchange to the ambient air governed by Newton's Law of Cooling with heat transfer coefficients of α=23.0 W·m^{-2}·K^{-1} for one and α=8.0 W·m^{-2}·K^{-1} for the other surface and the edge of the glazing system respectively. The initial temperature of the whole glazing system is 20°C. The material data used for the instationary temperature field calculations are shown in table 1.

Table I. Material data for the instationary temperature field and thermal stress calculations.

quantity	unit	glass	polymer foil
mass density ρ	kg·m^{-3}	2350	900
thermal conductivity λ	W·m^{-1}·K^{-1}	0.81	0.25
specific heat capacity c_p	kJ·kg^{-1}·K^{-1}	0.72	1
Young's modulus E	N·m^{-2}	7.0×10^{10}	1.5×10^{6}
Poisson's ratio ν	-	0.23	0.49
coefficient of linear thermal expansion α	K^{-1}	8.2×10^{-6}	120×10^{-6}

The geometrical cases computed are sketched in Fig. 7 with partly shadowed areas hatched.

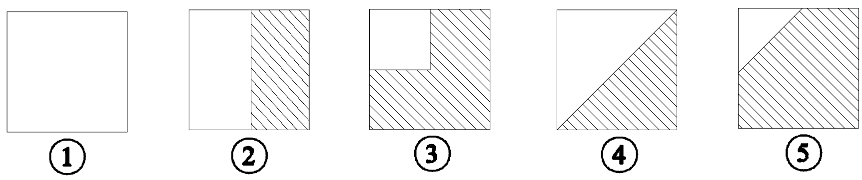

Fig. 7. Partly shadowed cases.

The resulting 3-dimensional temperature fields calculated with help of the finite element analysis software Abaqus Standard [4] are exemplarily shown for the cases 2, 3 and 5 in Fig. 8, 9 and 10. In any case the temperature field 20 minutes after the onset of irradiation is shown. At this time a maximum temperature difference between the warm and cold regions of the glazing of approximately 15 K is attained. At any point of time of the irradiation history the temperature gradient normal to the surface is less than 3 K over the 4.2 mm pane thickness. An electrochromic glazing at controlled states with higher solar transmittances than 0.06 obviously is expected to exhibit lower temperature differences.

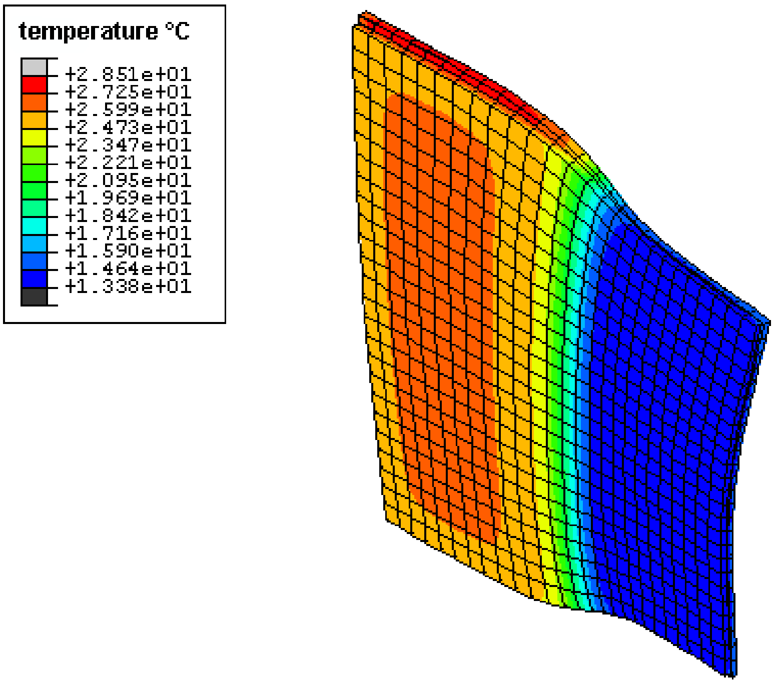

Fig. 8. Temperature field, case 2.

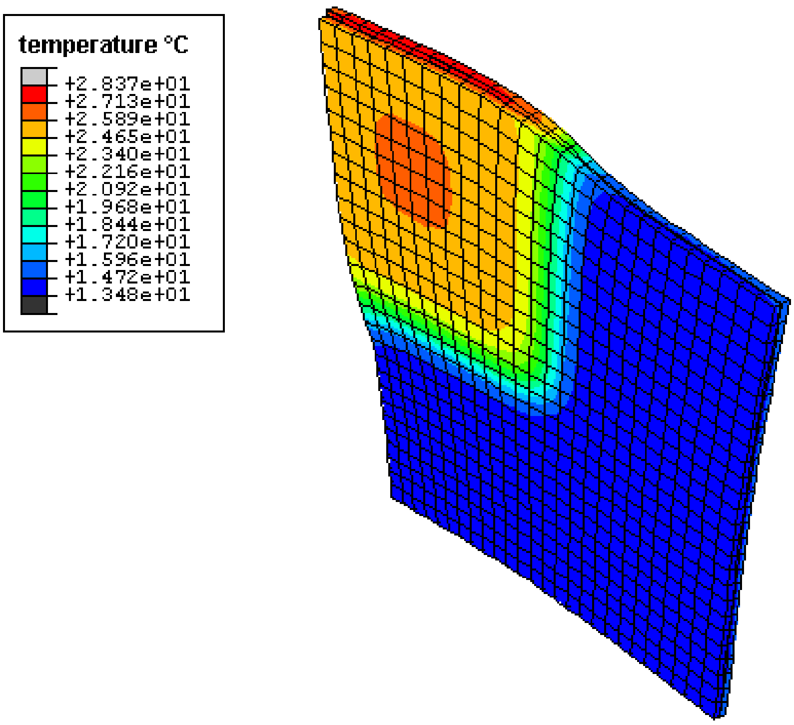

Fig. 9. Temperature field, case 3.

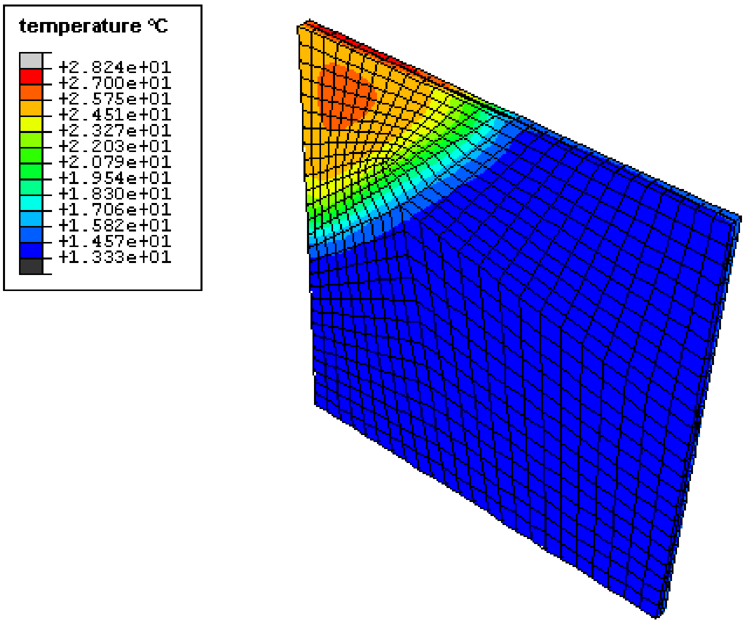

Fig. 10. Temperature field, case 5.

5. MECHANICAL STRESSES DUE TO SOLAR IRRADIATION

At any time of the transient irradiation period the three-dimensional temperature induced displacement and stress states were calculated. An elastic material model with the material constants listed in table 1 is considered. The linear thermal expansion coefficient of the glass was measured by means of a push-rod dilatometer (type Netzsch DIL 402). The maximum principal stresses according to the temperature fields of Fig. 8, 9 and 10 are illustrated in Fig. 11, 12 and 13.

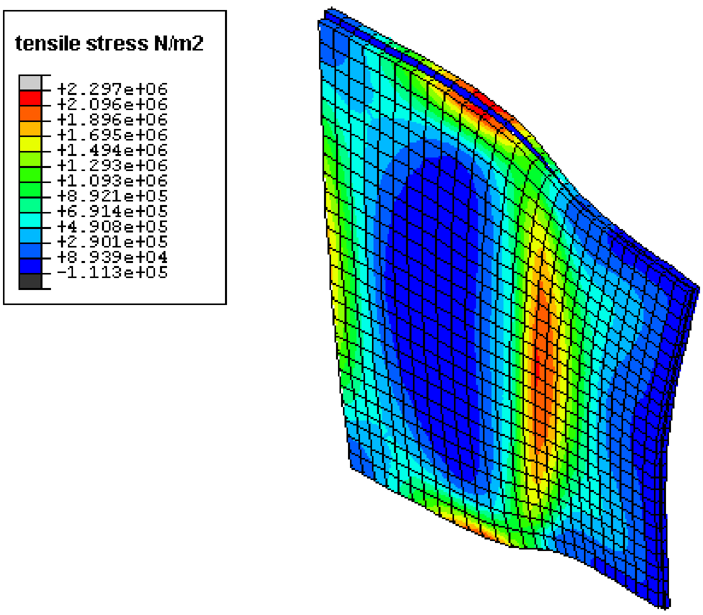

Fig.11. Maximum tensile stress, case 2.

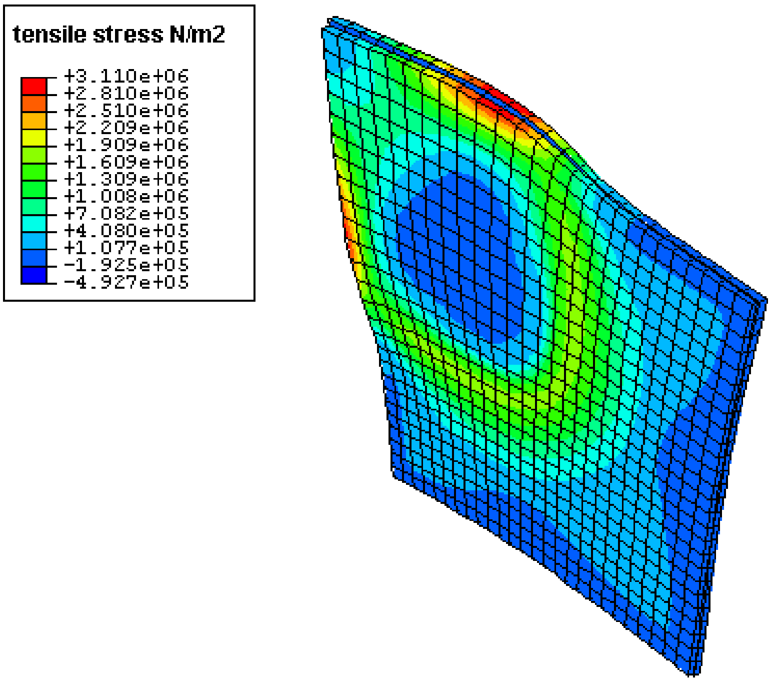

Fig.12. Maximum tensile stress, case 3.

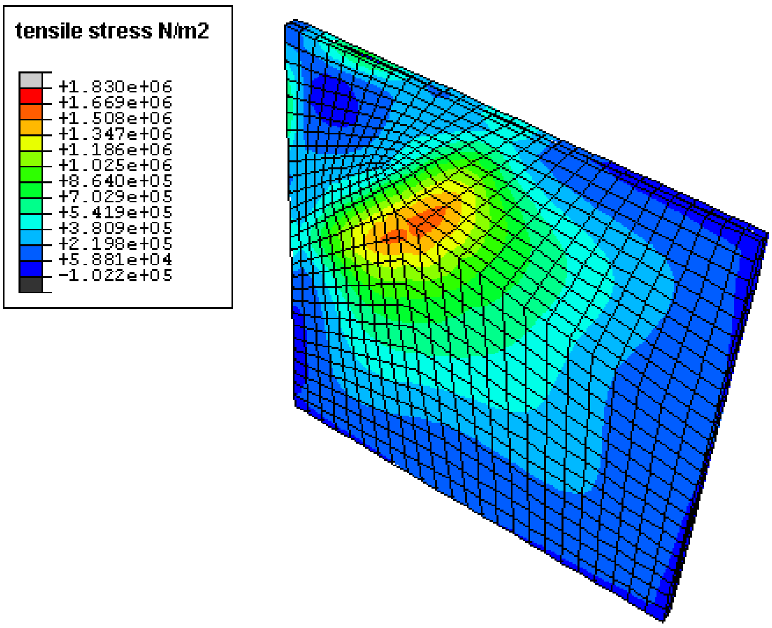

Fig.13. Maximum tensile stress, case 5.

The maximum tensile stresses occur both at the edges of the glass pane and near the shadow borderline. The stress direction lies in the glass plane. For the estimation of cracks only tensile stresses are important. A value of 3.11×10^6 N·m^{-2} appears in case 3 with a quarter of the glass area irradiated. In cases with a straight shadow borderline the maximum tensile stresses are smaller. In either case the tensile stresses are less than the glass tensile strength of 30×10^6 N·m^{-2}. For a better visualisation the deformation is displayed with a scale factor of 2000 (case 2 an 3) and 150 (case 5) respectively.

6. CONCLUSIONS

In this paper we have presented the transmittance and reflectance data in the wavelength range from 280 nm to 2500 nm of an electrochromic glazing with voltage controlled transmittance. The full colored and bleached state respectively were measured. We found a maximum change of 46 % for the solar transmittance as well as of 69 % for the visible transmittance. Furthermore the time dependent transmittance and reflectance at 380 nm to 780 nm meanwhile a coloring and bleaching cycle were measured.

Based upon the gained data the instationary temperature fields due to transient solar irradiation were calculated. Several cases with partly shadowed glass pane areas were considered. After all the temperature induced stresses were computed. In neither case the maximum tensile stresses exceed the tensile strength of the glass material. The maximum tensile stresses are an order of magnitude less than the tensile strength. Consequently the electrochromic glazing system is expected to work damage free under the considered irradiation circumstances.

ACKNOWLEDGEMENT

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